

Chapter 2

3D Food Printing Technologies and Factors Affecting Printing Precision

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2.1 INTRODUCTION

Three-dimensional (3D) printing, also known as additive manufacturing solid free-form fabrication, was first introduced in the food sector by researchers from Cornell University using an extrusion-based printer (Fab@home) (Periard et al., 2007). This technology is characterized by a layer-by-layer material deposition mode based directly from a predesigned file (Pinna et al., 2016; Rayna and Striukova, 2016).

There are many potential advantages of 3D printing technology applied to the food sector, such as customized food designs, personalized and digitalized nutrition, simplifying the supply chain and broadening the source of available food material. Using this technology, some complex and fantastic food designs which cannot be achieved by manual labour or conventional mould can be produced by ordinary people based on predetermined data files that comprise culinary knowledge and artistic skills from chefs, nutrition experts and food designers (Sun et al., 2015c, 2018). It also can be used to customize confectionery shapes and colourful images onto surfaces of solid edible substrates (Young, 2000; Zoran and Coelho, 2011).

In addition, 3D food printing permits digitisation and personalisation of the nutrition and energy requirements of an individual person according to their physical and nutrition status (Severini and Derossi, 2016; Sun et al., 2015c; Wegryzn et al., 2012; Yang et al., 2015). The conventional food supply chain can be simplified by 3D food printing. The universal application of this technique will make the manufacturing activities slowly move to places closer to the customers and will lead to reduced transport volume, thus reducing the packaging, distribution and overriding costs (Chen, 2016; Jia et al., 2016; Sun et al., 2015a,b,c). Food printing technology will also broaden the source of available food material by using nontraditional food materials such as insects, high-fibre plant-based materials and plant- and animal-based by-products (Payne et al., 2016; Severini and Derossi, 2016; Tran, 2016). Currently, 3D printing techniques available in the food sector generally include four types: extrusion-based printing, selective sintering printing (SLS), binder jetting and inkjet printing. This will be discussed in the chapter.

2.2 3D FOOD PRINTING TECHNOLOGIES AND FACTORS AFFECTING PRINTING PRECISION

As mentioned earlier, the quality and precision of printed objects depend on the materials' properties, processing factors and postprocessing treatments. Each 3D food printing technique has its own advantages and limitations. Table 2.1 shows the comparison of different 3D printing techniques and factors affecting the printing precision and accuracy. This is discussed in detail in the following.

TABLE 2.1 Comparison of Different 3D Food Technologies

		Extrusion-Based Printing	Selective Laser Sintering	Binder Jetting	Inkjet Printing
	Available material	Chocolate, soft material such as dough, cheese, meat puree	Powdered materials such as sugar, chocolate, fat	Liquid binder and powdered materials such as starch, sugar, protein	Low-viscosity material such as pizza sauce
Factors affecting printing precision	Material properties	Rheological properties, mechanical strength, Tg	Melting temperature, flowability, particle size, wettability, Tg	Flowability, particle size, wettability and binder's viscosity and surface tension	Compatibility, ink rheological properties, surface properties
	Processing factors	Printing height, nozzle diameter, printing rate, nozzle movement rate	Laser types, laser power, laser energy density, scanning speed, laser spot diameter, laser thickness	Head types, printing rate, nozzle diameter, layer thickness	Temperature, printing rate, nozzle diameter, printing height
	Postprocessing	Additive, recipe control	Removal of excess parts	Heating, baking, surface coating, removal of excess parts	No
	Advantages	More material choices, simple device	Complex 3D food fabrication, varying textures	Complex 3D food fabrication, full colour potential, varying flavours and textures	More material choices, better printing quality, fast fabrication

Continued

TABLE 2.1 Comparison of Different 3D Food Technologies—cont'd

		Extrusion-Based Printing	Selective Laser Sintering	Binder Jetting	Inkjet Printing
	Limitations	Incapable of fabricating of complex food designs, difficult to hold 3D structures in postprocessing	Limited materials, less nutritious products	Limited material, less nutritious products	Simple food design, only for surface filling or image decoration
	Products				

The products images were reproduced from the websites: (a) Natural Machines Co., available at <https://www.naturalmachines.com/>; (b) CandyFab Project, available at <https://candyfab.org/TNO>; (c) 3D Systems Co., available at <https://www.3dsystems.com/culinary/gallery>; (d) FoodJet Printing Systems, available at <http://www.foodjet.com/>.

2.2.1 Extrusion-Based Printing

Extrusion-based printing, first known as fused deposition modelling, was first introduced to fabricate plastics products (Ahn et al., 2002). During the food printing process, the melted material or pastelike slurry is extruded out continuously from a moving nozzle and welds to the preceding layers on cooling. According to the temperature used in the deposition process, extrusion-based printing can be classified into melting extrusion-based printing and soft materials extrusion-based printing.

2.2.1.1 Melting Extrusion-Based Printing

Melting extrusion-based printing has been widely applied to create customized 3D chocolate products (Hao et al., 2010; Mantihal et al., 2017). During the printing process, melted semisolid food polymer is extruded from a movable printhead and solidifies and welds to the previous layers almost immediately after extrusion.

2.2.1.1.1 Mechanism of Formation of Self-Supporting Layers

In melting extrusion of chocolate, understanding the properties of the chocolate is critical to the quality of the printed objects due to the complex compositions and six different crystalline phases of cocoa butter (Marangoni and McGauley, 2003). The chocolate ink should be able to hold its structure during and after the layer-by-layer deposition process. This ‘self-supporting’ capacity relies on thermal properties like glass transition temperature (T_g) and melting point, which is critical in the postdeposition solidification process of the deposited layer (Mantihal et al., 2017).

2.2.1.1.2 Effect of Printing Parameters on Printing Behaviour

The processing parameters, such as nozzle diameter, nozzle height, extrusion rate and nozzle moving speed, are also critical to the quality of the resulting printed constructs in melting printing process. Previous work (Hao et al., 2010) on the deposition of chocolate showed that the distance between the nozzle tip and build platform played an important role in the quality of built objects. This study showed that when a lower nozzle height than optimal height was applied, the volume of the extruded chocolate was too large for the space between the building platform and nozzle. Thus, the slurry was forced to spread in directions perpendicular to the deposited slurry line, and the resultant extruded objects displayed a squeezing effect and poor accuracy. Conversely, the application of a larger nozzle height, resulting in parts of the chocolate not reaching the marble build surface in time, led to massively inaccurate parts (Hao et al., 2010). The printing accuracy was also seriously affected by the extrusion rate and nozzle movement rate due to the bead diameter of chocolate track that decreased with the nozzle movement rate while increasing with the

extrusion rate (Hao et al., 2010). Temperature is also a critical factor to achieve successful hot melting extrusion printing, especially for chocolate printing (Mantihal et al., 2017).

2.2.1.1.3 Implications of Materials' Thermal Properties on Melting Extrusion-Based Printing

Temperature is a critical factor to a successful melting printing. Hao et al. (2010) investigated the material characterization on the quality of printed objects. During this process, a seed was added in the premelted chocolate to generate more V crystals which was desirable in the deposition of 'good' chocolate. Chocolate slurries with pseudoplastic properties at different temperatures were highly desirable in the deposition of 3D constructs (Hao et al., 2010). There are six major crystal polymorphs' formation in cocoa butter. Form V, with melting temperature (T_m) ranging between 33.8 and 35°C, is the most important crystal and will give the final chocolate product more stable characteristics, a glossy finish and better texture. Thus, a proper and careful manipulation of the heat treatment is vital to gain Form V crystal (Mantihal et al., 2017). Mantihal et al. (2017) concluded that 32°C is the optimum temperature for chocolate printing with addition of magnesium stearate where most of the stable crystals are formed.

2.2.1.1.4 Application of Melting Extrusion-Based Printing in Food Creation

The melting printing of chocolate was first conducted using a Fab@home system. Processing factors like temperature and extrusion rate affecting the printing accuracy during chocolate fabrication were investigated (Hao et al., 2010). The chocolate extrusion printing has been commercialized by Choc Edge's Choc Creator, 3D System's ChefJet, Hershey's CocoJet and Chocabyte (Millen, 2012; Zhuo, 2015). A melting extrusion-based printer has been created by Natural Machines to be used for chocolate printing (Galdeano, 2015). Researchers from Massachusetts Institute of Technology used melting chocolate as a dispensing liquid and developed a printer named 'Digital Chocolatier' (Young, 2000; Zoran and Coelho, 2011). Mantihal et al. (2017) investigated the correlation of 3D chocolate printing behaviour with thermal properties and concluded that the application of 32°C showed the best performance.

2.2.1.2 Soft Materials Extrusion-Based Printing

During the soft materials extrusion-based printing process, the pastelike food slurry is extruded out continuously from a moving nozzle and welds to the preceding layers on cooling, such as dough, mashed potatoes (MP), cheese and meat paste (Lipton et al., 2010; Yang et al., 2015). Three extrusion mechanisms have been applied in 3D food printing: screw-based extrusion, air

pressure-based extrusion and syringe-based extrusion. In the screw-based extrusion process, food materials are put into the sample feeder and transported to the nozzle tip by a moving screw. During the extrusion process, food materials can be fed into the hopper continuously, thus realizing the continuous printing. However, the screw-based extrusion is not suitable for the food slurry with high viscosity and high mechanical strength; thus, the printed samples do not attain proper mechanical strength to support the following deposited layers and result in compressed deformation and poor resolution (Liu et al., 2018). The air pressure-based extrusion, during which food materials are pushed to the nozzle by air pressure, is suitable to print liquid or low-viscosity materials (Sun et al., 2018). The syringe-based extrusion unit is suitable to print food materials with high viscosity and high mechanical strength so that it probably can be used to fabricate complex 3D structures with high resolution. Some printed samples with a syringe-based printer are illustrated in Fig. 2.1 (Liu et al., 2018). However, it should be noted that the air pressure-based extrusion and syringe-based extrusion do not allow the continuous feeding of food materials during printing.

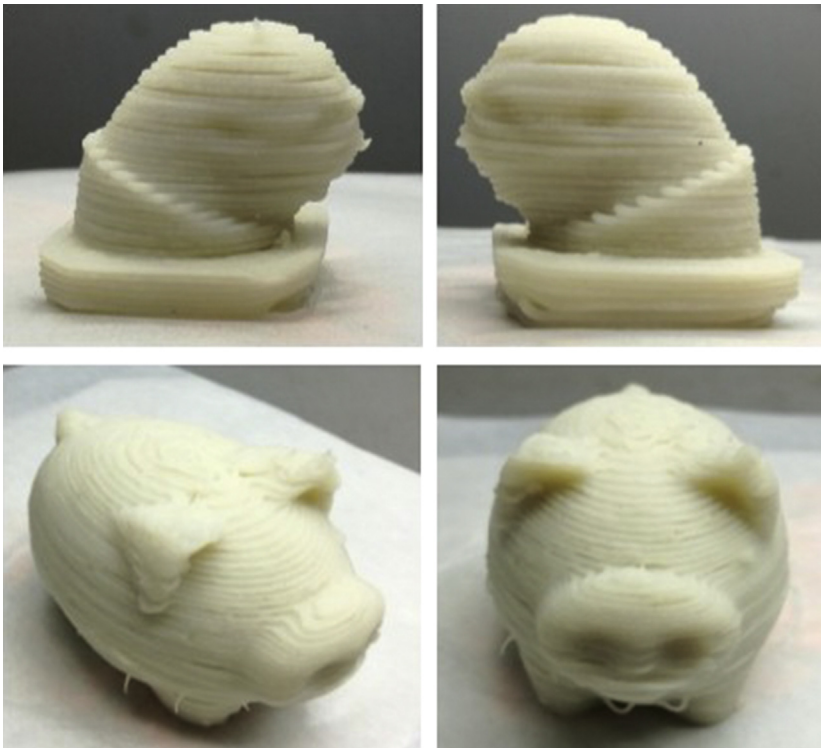


FIGURE 2.1 Printed objects using mashed potatoes with a syringe-based printer (Liu et al., 2018).

2.2.1.2.1 Mechanism of Formation of Self-Supporting Layers

Though soft materials extrusion-based printing has been applied in the deposition of a wide variety of soft materials, the deposition of them into complex and delicate shapes is inherently limited, as they are fundamentally prone to distortion and warping. To fabricate delicate and complex shapes during the soft material extrusion process, it is necessary to print the additional structural objects to support the product geometry. The supporting constructs must be manually removed in the final stage. This is a time-consuming process and will slow printing speed and raise material costs (Von Hasseln, 2013; Von Hasseln et al., 2014; Von et al., 2015b). Therefore, it is necessary to fully understand the material properties and relevant technologies to be able to thus construct 3D structures. The highly desirable soft materials for extrusion 3D printing should not only possess suitable mechanical strength (yield stress and elastic modulus) to be capable of maintaining printed shapes, but also have shear-thinning behaviour to be easily extruded out from the nozzle tip in an extrusion-based type printer. A good balance must be made so that the mixture is as strong as possible to maintain the printed shape while it still could be printable and capable of adhering to previously deposited layers (Liu et al., 2018).

2.2.1.2.2 Effect of Printing Parameters on Printing Behaviour

The effect of printing parameters on 3D printing behaviour has been investigated by many researchers (Wang et al., 2018; Yang et al., 2018). The application of a nozzle height lower than optimum height led to thicker extruded lines than intended, while a higher height led to parts of the extruded surimi lines not reaching the build surface before the nozzle turned a corner and thus resulted in massively inaccurate sections (Wang et al., 2018). The effect of various nozzle diameters on the built construct was simple to determine. A safe rule of thumb is to select the smallest nozzle tip that allows for easy material extrusion, as it is helpful to construct the object with the finest resolution and smooth surface during printing (Periard et al., 2007). Wang et al. (2018) concluded that the nozzle diameter affected the printing precision and surface smoothness considerably. The 3D printing of fish surimi displayed that the application of a small nozzle diameter (0.8, 1.5 mm) led to relatively poor models due to the inconsistent extruded surimi filament in its diameter along the length. Conversely, the use of a larger nozzle diameter could extrude consistent lines, but the resolution and accuracy of the objects were poor (Wang et al., 2018). Generally, a small nozzle diameter is beneficial to print objects with fine resolution, but it should be noted that the printing time required increased greatly when using a small nozzle size. A good balance must be made with the printing productivity and the printing precision. The extrusion rate and nozzle moving speed are also important in

extrusion-based printing. It was suggested that the critical nozzle movement rate can be determined by Eq. 2.1 (Khalil and Sun, 2007):

$$v_N = \frac{4Q}{\pi D_N^2} \quad (2.1)$$

where v_N is the optimal nozzle speed (mm/s), Q the material flow rate (cm³/s) and D_N the nozzle diameter. It was shown that a nozzle velocity greater than v_N would result in a smaller-diameter material bead than that of the nozzle, whereas a nozzle velocity less than v_N would lead to a greater-diameter material bead than that of the nozzle. Neither of them were desired in printing (Khalil and Sun, 2007). Wang et al. (2018) suggested that the alteration of nozzle speed would affect the critical nozzle height when all other parameters were kept constant. Too-high speed (32 mm/s) resulted in the dragging effect, causing breaking of the extruded slurry filaments, while too-low moving speed (20 mm/s) resulted in the occurrence of flow instabilities of slurry and the formation of coils. They also suggested that there is a linear relationship between the extrusion rate and the diameter of surimi lines. Too-high extrusion rate (0.004 cm³/s) gave a larger extruded lines' diameter than desired due to the extrusion of greater volume of material. Too-low extrusion rate (0.002 cm³/s) led to an inconsistent surimi slurry (Wang et al., 2018). In previous work (Zhuo, 2015) on the development of a 3D food printer, a positive linear relationship between nozzle moving speed and extrusion rate was studied (Zhuo, 2015).

The printing temperature should also be fine-tuned, as the viscosity of the food material is directly correlated with the temperature. In the previous work of 3D printing Vegemite and Marmite (Hamilton et al., 2018), the viscosity decreased when the temperature increased. To extrude both materials at 25°C, 172 kPa of pressure was used, but it should be decreased to 103 kPa at 45°C. The application of a 172 kPa pressure to fabricate objects at 45°C led to too-large flow rate and the formation of a puddle of material. With a further increase of temperature to 65°C, too-quick extrusion of the material was formed even with the application of a very low pressure (<34 kPa) (Hamilton et al., 2018).

2.2.1.2.3 Effect of Materials' Properties of Soft Materials on Printing Behaviour

In extrusion-based printing, the properties of food material, such as the moisture content, rheological properties, specific cross-linking mechanisms and thermal properties, are critical to a successful printing. The viscosity of the soft material should be both low enough to be easily extruded through a fine nozzle and high enough to hold the subsequently deposited layers (Godoi et al., 2016). Wang and Shaw (2005) concluded that dental porcelain slurries with shear-thinning behaviour are beneficial to the construction of objects, as

they can be easily extruded out from the nozzle with the application of shear stress, and they become rigid and solidify upon the departure from the extruder (Wang and Shaw, 2005). In our previous work (Liu et al., 2018), we investigated the impact of rheological properties of MP on 3D printing by addition of different concentrations of potato starch (PS). We concluded that the highly desirable materials for 3D food printing should not only possess suitable yield stress (τ_0) and elastic modulus (G') to be capable of maintaining printed shapes, but also have relative low consistency index (K) and flow behaviour index (n) to be easily extruded out from the nozzle in an extrusion-based type printer. MP with an addition of 2% PS displayed excellent extrudability and printability, i.e., shear-thinning behaviour, K of 118.44 ($\text{Pa} \cdot \text{sn}$), and strong-enough mechanical strength with τ_0 of 312.16 Pa and proper G' ; therefore, the objects could withstand the shape over time and possessed smooth shape and resolution. No addition of PS induced a drop in τ_0 (195.90 Pa) and G' ; thus, printed objects deformed in time because of sagging. Although MP with an addition of 4% PS represented good shape retention due to proper τ_0 (370.33 Pa) and G' , the poor extrudability made it difficult to print due to high K (214.27 $\text{Pa} \cdot \text{sn}$) and viscosity. The printed samples are illustrated in Fig. 2.2 (Liu et al., 2018). In addition, our research group studied the fish surimi gel as potential food material for 3D printing (Wang et al., 2018). Results indicated that the surimi with high viscosity and low loss tangents ($\tan\delta = G''/G'$) could

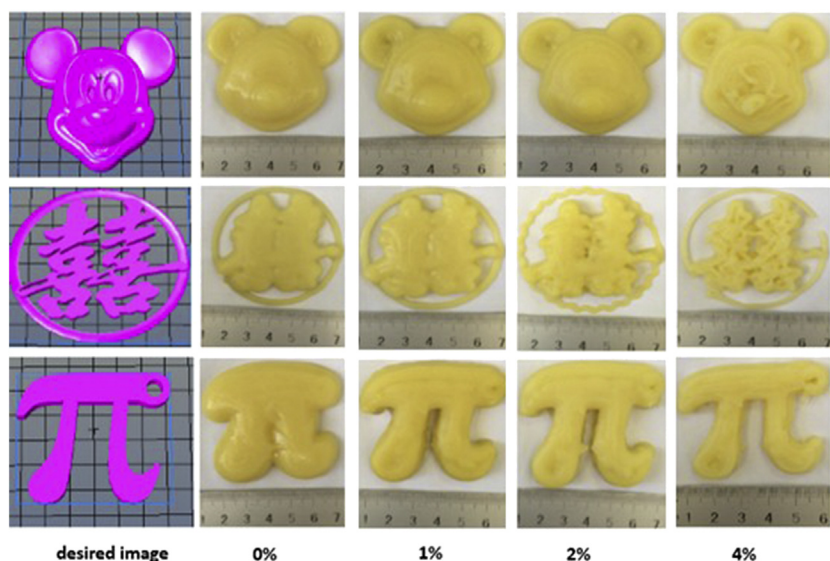


FIGURE 2.2 Desired images and printed objects using mashed potatoes with addition of different concentrations of potato starch (Liu et al., 2017, 2018).

not be extruded smoothly, with large amounts of broken deposited lines. NaCl could be used to adjust the viscoelasticity of surimi and the printed objects; using surimi with an addition of 1.5/100g NaCl displayed a smooth surface structure, better matching with the target geometry and no compressed deformation (Wang et al., 2018).

In the previous work of 3D printing of Vegemite and Marmite, Hamilton et al. (2018) indicated that the n and K were critical in determining whether a material is suitable for 3D printing and determining the desired extrusion rates. Zhang et al. (2015) also reported that the gel with higher τ_0 and G' revealed better performance to support the additional deposited layers in the printing of dual-responsive hydrogels. To achieve an ideal rheological property to be capable of holding the 3D structures, rheological modifiers, such as hydrocolloids and soluble protein, can be added but must comply with food safety standards. In addition, the crystallization state and T_g of material is also critical to make the deposited material able to support its own structure after printing (Godoi et al., 2016).

2.2.1.3 Pre- and Posttreatment Methods

Ideally, the 3D food structures should be resistant to postprocessing (baking, cooking, frying, etc.), as most of the foods consumed in daily life must go through these processes. The deposition of various kinds of soft material, such as cookie dough, cheese and cake frosting, has been done via the extrusion-based 3D printing technique (Lipton et al., 2010). However, these objects were not suitable for conventional food processing techniques and would be greatly deformed after postprocessing treatments. In order to realize the wide application of the 3D printing process on foods, this technique must be easily compatible with traditional food processing steps (Lipton et al., 2015). Two main ways that have been applied to maintain the shape stability of objects after postprocessing are recipe control and addition of additives (Lipton et al., 2010). Additives of various concentrations of transglutaminase were blended with lean beef paste to maintain printed shape stability after cooking. It was shown that addition of 0.5% of transglutaminase by weight significantly increased the structure stability after cooking. This was because the addition of transglutaminase led to the formation of a new protein matrix over time. The shape retention of printed scallop meat through deep fried and turkey meat through sous-vide cooking were investigated, and excellent performances were obtained (Lipton et al., 2010). In another study, the composition of the cookie recipe was found to have significant effects on the printability and shape stability of the cookie. It was shown that increasing the butter content increased the printability but decreased the shape stability after baking. The increase of yolk concentrations increased the shape stability (Lipton et al., 2010). The method of varying recipe formulation of cookie dough to achieve desired printability and shape stability after baking has also been investigated

(Zhuo, 2015). Godoi et al. (2016) believe that the 3D printed structures which can resist postprocessing can be achieved by controlling the physical–chemical, rheological, structural and mechanical properties of the materials.

2.2.1.4 Application of Soft Materials Extrusion-Based Printing in Food Creation

Researchers from Cornell University studied the fabrication of cake frosting, processed cheese and sugar cookies using extrusion-based printing (Lipton et al., 2010; Periard et al., 2007). This technology has also been applied by the Netherlands Organization for Applied Scientific Research (TNO) to fabricate various kinds of foods using traditional materials and nontraditional ingredients such as algae and insects (Daniel, 2015; Sol et al., 2015). Another extrusion-based printer (Foodini Printer) has been created by Natural Machines to be used for surface filling and graphical decoration (Galdeano, 2015). Camille et al. (2018) studied the effect of 3D printing on quality of processed cheese. Many kinds of food materials have been printed using extrusion-based printing technology, such as lemon juice gel (Yang et al., 2018), processed cheese (Camille et al., 2018), pectin gel (Vancuawenberghe et al., 2017), MP (Liu et al., 2018), fish surimi gels (Wang et al., 2018), fruit-based snacks (Derossi et al., 2018), chocolate (Mantihal et al., 2017) and many other food products (Hamilton et al., 2018; Holland et al., 2018; Kouzani et al., 2017; Lanaro et al., 2017; Lille et al., 2018; Liu et al., 2017; Schutyser et al., 2018; Severini et al., 2016).

2.2.2 Selective Laser Sintering

Selective laser sintering (SLS) is a technology that applies a power laser to selectively fuse powder particles together layer by layer finally into a 3D structure. The laser scans cross-sections on the surface of each layer and selectively fuses the powder. After scanning each cross-section, the powder bed is dropped, and a new layer of powder is covered on top. This process is repeated until the desired structure is finished. Finally, the unfused powder is removed and reclaimed for next printing (Noort et al., 2016). SLS has been widely applied in metal and ceramic industrial manufacturing; however, there are several hurdles to using SLS in the food sector: (1) suitable powdered material which can fuse together without decomposition of the material itself during fabricating process; and (2) the construction of various edible objects using a wide range of food materials (Diaz et al., 2014). Generally, SLS allows for the production of freestanding complex 3D structures with high resolution, but the available material is limited to powder material, such as sugar, fat or starch granule. It is necessary to expand the available range of food ingredients to thus broaden the application of this technology in traditional food.

2.2.2.1 *Effect of Printing Parameters on Printing Behaviour*

The processing factors, such as laser types, laser diameter, laser power and scanning speed, should also be fine-tuned to get a desired outcome. The interaction between the powdered materials and laser beam is critical to the quality of fabricated constructs in SLS process, as the strength of interaction depends on the laser types, and the fusion of material is affected by the laser energy density (Gu et al., 2012). A higher laser energy density, which can be obtained by adjusting the scanning speed and laser power, leads to denser parts with stronger mechanical strength due to longer interaction time. A porous and brittle structure will be obtained when a lower laser energy density is applied (Fred et al., 2014). The CandyFab uses hot air to selectively sinter and melt sugar powder due to the low T_m of sugar powder. The interaction time between the hot air gun and sugar powder was 1 to 3 s, determined by the air temperature and layer thickness. Larger laser spot diameter made the constructs less likely to break, and a higher rate of fabrication was obtained by turning up the heat and speed, while the resulting object's precision and resolution were poor. Changing the laser diameter from 5 mm to about 1.6 mm improved the printing resolution and precision, but at the expense of lowering the constructing rate and reducing the mechanical strength of the printed object (CandyFab, 2009). In the fabrication of an colourful and detailed edible object, the SLS procedure was performed by Diaz et al. (2014) using a carbon dioxide laser with laser spot diameter 0.6 mm and specific process parameters (layer distance of 0.1 mm, writing speed 1250 mm/s, laser power 50% and layer thickness 0.3 mm).

2.2.2.2 *Implications of Materials' Properties on Laser-Based Printing*

Materials' properties, such as particle size, flowability, bulk density and wettability of powder material, have a great impact on the printing precision and accuracy of objects in SLS (Godoi et al., 2016). Powder density and compressibility are also important in SLS, as they seriously affect the powder flowability inside the vessel which, in turn, contributes to the formation of patterns when the laser source is applied to the powder bed (Berretta et al., 2013; Schmid et al., 2013). The preferred edible powder in SLS should be a free-flowing powder which can be poured without substantial clumping. In addition, the powdered material should not be sticky and thus has no or any tendency to agglomerate or to adhere to contact surfaces (Diaz et al., 2014). The particle size affects the printing precision and resolution of fabricated objects (Duan et al., 2010; Sun et al., 2015a). A smaller layer thickness results in a stronger mechanical strength and a decrease in the porosity of fabricated constructs, while the minimum layer thickness that can be used in SLS is determined by the maximum particle size of the powder (Fred et al., 2014). Diaz et al. (2014) invented a method for the production of edible objects with a

high degree of resolution and precision using SLS. In this invention, the multimaterial structures were created by using a powder composition comprising a structural element and a binder component. The structural element provided bulk and scaffold function, and the binder component acted as particle-particle sintering, helping bind the powder into the desired structure. Typically, the T_m or T_g of the binder component ranged between 10 and 200°C. The binder should undergo melting and glass transition in less than 5 s, while the structural component should be nonmelting at the temperatures below 200°C (Diaz et al., 2014). In addition, they concluded that the binder comprising at least two compounds that differ in their T_g or T_m , such as the palm oil powder with a T_m of 30°C and maltodextrin with a T_g of 62°C, demonstrated excellent performance in aspects of the printing precision and accuracy of printed objects.

2.2.2.3 Application of Laser-Based Printing in Food Creation

SLS has been utilized to fabricate complex structures using sugar or sugar-rich powders. Delicate and complex 3D structures have been created by researchers from TNO using sugars and NesQuik powders (Gray, 2010). Using SLS, CandyFab Project has successfully created various attractive complex structures using sugar powders which could not be produced by conventional ways (CandyFab, 2007).

2.2.3 Binder Jetting

Binder jetting printing, also known as inkjet 3D printing, was first introduced by Sachs et al. (1994), during which powdered materials were deposited layer by layer and the binder was selectively ejected upon each material layer at certain regions based on the data file for the object being produced. The binder fuses the current cross-sections to previous and afterward fused cross-sections. The unfused powder supported the fused parts at all times during the fabrication process, allowing for the production of intricate and complex structures. Finally, the unbound powder is removed and recycled for further use (Sachs et al., 1994). Binder jetting technology can be used to fabricate complex and delicate 3D structures and has the potential to produce colourful 3D edible objects by varying binder composition. However, the structural material is only limited to powder stuff, and the edible binder affects its wide application in the food sector, especially in the field of traditional food consumed in daily life.

2.2.3.1 Effect of Printing Parameters on Printing Behaviour

The processing factors, such as head types, printing velocity, droplets' path, nozzle diameter and resonance frequency of the head, affect the precision of printed objects. In general, a larger nozzle diameter helps to increase printing

speed but reduces the resolution and precision of fabricated objects (Shirazi et al., 2015). In order to realize a successful printing, the processing factors mentioned above should be properly adjusted.

2.2.3.2 *Implications of Materials' Properties on Binder Jetting*

In the binder jetting process, properties of powdered material and the binder are critical to the successful fabrication of parts. The binder must have suitable viscosity, surface tension, ink density and suitable properties to prevent spreading from nozzles. The binder concentration was also important for the successful fabrication of parts with desired dimensional precision (Peters et al., 2006). In a successful fabrication process, the bound structures should possess adequate product strength with minimal shrinkage or expansion and minimal 'bleeding' of the binder into neighbouring voxels (Von Hasseln, 2013; Von Hasseln et al., 2014; Von et al., 2015a). Flowability of powder is important. The powder with suitable flowability permits the roller to easily build up thin layers, which facilitates the fabrication with high precision and accuracy. Conversely, poor flowability reduces the resolution and accuracy of fabricated parts due to insufficient recoating (Lanzetta and Sachs, 2003). A free-flowing powder with suitable spreading and packing properties is preferred in binder jetting. It means that the powder should be not sticky and thus has hardly any or no tendency to agglomerate or to adhere to contact surfaces. Typically, the angle of repose of the powder should be low, e.g., smaller than 30 degrees (Diaz et al., 2015). The wettability of powder is another affecting factor in accurate printing. It has been suggested that too-low wetting of powder material leads to the rearrangement of powder bed that is detrimental to subsequent printing. Too-high wetting and slow reaction between powder and binder reduce the resolution of and precision of fabricated objects (Hogekamp and Pohl, 2004; Shirazi et al., 2015). The moisture content of edible powder used in binder jetting should be less than 6%, based on the powder material composition (Von et al., 2015b). In addition, wetting methods have also been applied to reduce the unbound powder migration during the fabrication process (Hunter et al., 2008). The particle size and distribution of powders also affect the printing precision and accuracy, as the variation of particle size influences the pore size distribution within the powder bed and thus affects the binding behaviour of a water-based binder (Hapgood et al., 2002; Von et al., 2015a). To achieve an edible powder with suitable spreading and packing qualities, coarse powder particles can be mixed with fine powder particles (Von Hasseln, 2013; Von Hasseln et al., 2014; Von et al., 2015a).

2.2.3.3 *Application of Binder Jetting in Food Creation*

Binder jetting offers advantages such as fast fabrication, building of complex structures and low material cost (Sun et al., 2015a). Based on binder jetting, Southerland and Walters (2011) investigated the fabrication of edible

constructs using sugars and starch mixtures. Researchers from 3D System have created a binder to produce a wide variety of colourful and flavourful edible objects, such as various kinds of complex sculptural cakes, by varying flavour and colourful binders (Izdebska and Tryznowska, 2016).

2.2.4 Inkjet Printing

Inkjet printing dispenses a stream of droplets from a thermal or piezoelectric head to certain regions for the surface filling or image decoration on food surfaces, such as cookie, cake and pizza (Kruth et al., 2007). There are two types of inkjet printing methods: continuous jet printing and drop-on-demand printing. In a continuous jet printer, ink is ejected continuously through a piezoelectric crystal vibrating at a constant frequency. To get a desired flowability of the ink, it is charged by the addition of some conductive agents. In a drop-on-demand printer, ink is ejected out from heads under pressure exerted by a valve. Generally, the printing rates of drop-on-demand systems are slower than those of continuous jet systems, but the resolution and precision of produced images are higher. A typical maximum resolution for a single-printhead continuous jet printer image is about 70–90 dots per square inch (dpi) (Willcocks et al., 2011). Generally, inkjet printing handles low-viscosity materials that do not possess enough mechanical strength to hold a 3D structure. Therefore, it is usually used to print two-dimensional images. From the point of view of printing precision and accuracy, the compatibility between ink and substrate surface, viscosity and rheological properties of ink, temperature and printing rate are important to a successful printing.

2.2.4.1 Effect of Printing Parameters on Printing Behaviour

The viscosity and rheological properties of edible ink are also critical to the printing precision and accuracy (Godoi et al., 2016). Generally, it is necessary that the edible inks possess low viscosity so that they can be easily ejected through the tiny orifices of the printhead (Shastry et al., 2006). The desired inks in continuous jets have a narrow range of acceptable viscosity. The viscosity above 10 mPas easily leads to the pump's cavitation inside the printhead during printing. The ink with viscosity below about 2 mPas is not stable. Thus, the most desired viscosity of inks in a continuous jet printer should be between about 2.8 to about 6 mPas (Shastry et al., 2004). Willcocks et al. (2011) also suggested that the inks should possess ideal viscosity to enable the proper flowability (Willcocks et al., 2011). Temperature is another important factor in ink jetting, as it can be used to modify the rheological properties and surface energy of the inks. A low temperature may be applied to lower surface energy and reduce the spreading tendency of inks across the chocolate surface (Shastry et al., 2006; Willcocks et al., 2011). The temperature required to achieve desired viscosity also changes with the ink ingredients (Shastry et al., 2004).

2.2.4.2 *Implications of Materials' Properties on Binder Jetting*

The compatibility of the printed image with surfaces of substrates play a critical role in determining the final image quality and resolution. The surface chemistry of the substrates and that of the ink influence the interaction behaviour once the ink droplets are jetted onto the surface. Sometimes it is necessary to improve the compatibility of substrate's surface by coating the surface with a binder film or other compatibility-enhancing film before printing an image (Shastry et al., 2004, 2006; Willcocks et al., 2011). In the previous work (Mandery, 2010), a binder such as shellac or poly (1-vinyl-2-pyrrolidone) was added to the edible ink to increase the compatibility between the ink and the substrate (Mandery, 2010). Water-based glazes containing gums or other surfactants, such as polyglycerol oleates and polysorbates, were also used to modify the chocolate adequately to allow the printing of high-resolution images on surface. Moreover, with the application of multilayers of surfactant on the substrate surface before printing an image, the compatibility was significantly increased. Thus, the printed images were better with high printing precision and resolution (Willcocks et al., 2011). The contact angle of ink droplet on surface, closely related to the compatibility and adhesion between the ink and the substrate, is desired to be less than about 50 degrees. Another indication of the compatibility, surface tension of the inks, is most preferred below 35 dyn/cm (Shastry et al., 2004). Shastry et al. (2006) also indicated that a low-polarity material such as carnauba wax is typically coated on the surface of many hard-panned sugar shell confections, which shows an adverse effect on the printing of an image with high precision and accuracy due to the low-polarity surfaces. Thus, a hydrophilic substance was usually coated to the surface of substrates to form a polarity-modified surface to improve the compatibility of water-based ink with the substrate (Shastry et al., 2006).

2.2.4.3 *Application of Inkjet Printing Food Creation*

Inkjet printing generally handles low-viscosity materials; thus, it is mainly used in the area of surface filling or image decoration (Pallottino et al., 2016). Grood and Grood (2011) created an drop-on-demand inkjet printer to dispense edible liquids onto food surfaces to create appealing images (Grood and Grood, 2011). The FoodJet printer uses pneumatic membrane nozzle jets to deposit edible drops onto a moving object to form an appealing surface (FoodJet, 2015). Willcocks et al. (2011) created a kind of edible ink to fabricate high-resolution images on edible substrates such as biscuit, cake and crackers.

2.3 SUMMARY AND FUTURE DIRECTIONS

Recently, great efforts have been made by researchers aiming at applying 3D food printing into the food industry. However, there are still many difficulties for this technology to be widely used in the food sector due to

several reasons: (1) printing precision and accuracy, (2) process productivity and (3) production of colourful, multiflavour, multistructure products.

Printing precision and accuracy are critical to the application of 3D printing technology in the food sector. One of the advantages of 3D printing is to fabricate an exquisite and fascinating structure of edible products to increase consumers' interest and appetites. However, currently, few works focused on printing accuracy are published. To achieve a precise and accurate printing, material properties (i.e., rheological properties, particle size, etc.), process parameters (i.e., nozzle diameter, printing speed, printing distance, etc.) and postprocessing methods (i.e., baking, frying, cooking, etc.) should be kept in mind. More efforts should be given in the achievement of precise and accurate printing.

Improving production efficiency can reduce production costs. A common example of enhancing process productivity is to increase the printing speed and to use large nozzle or laser diameter. However, this often leads the reduction of precision and resolution of printed objects, thus placing 3D food printing in an unfavourable circumstance. We emphasize that under the premise of ensuring acceptable printing accuracy, a large nozzle diameter and fast printing speed should be adopted. Another potential way to improve printing productivity is to use multinozzle printers to fabricate multiple objects simultaneously. However, this will surely increase the complexity of the control system and be a technical challenge; thus, it is necessary to carry out considerable studies to achieve both accurate printing and high process productivity.

As the colour, flavour and texture of food are critical to the experience of people, it is necessary to fabricate a 3D edible structure with these desired attributes. Several attempts have been made in the production of colourful, varying flavour and texture of food products using extrusion-based printing (Fig. 2.3) and binder jetting technology (Von Hasseln, 2013; Von Hasseln

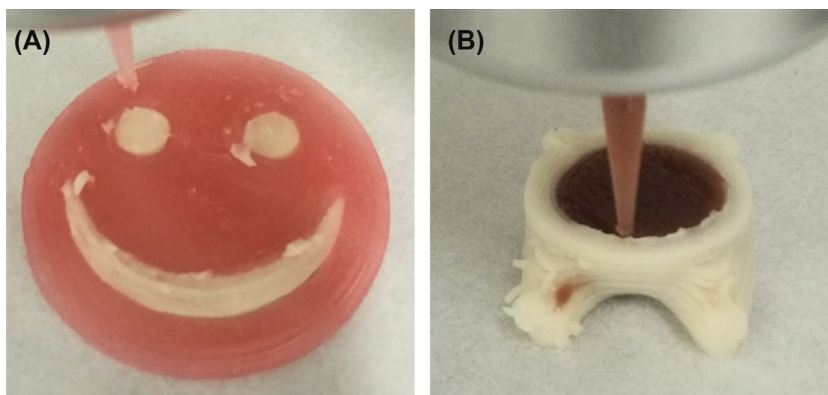


FIGURE 2.3 Some printed samples using extrusion-based printing (our group). (A) mashed potatoes and strawberry juice gel; (B) mashed potatoes and strawberry jam.

et al., 2014; Von et al., 2015a), but they have not been widely applied. Thus, more attention should be given to the production of varying colour, flavour and texture food products.

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